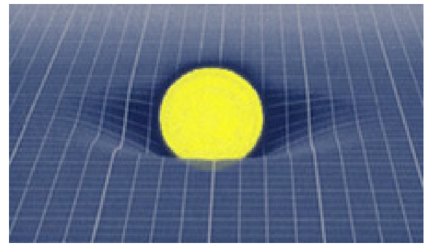
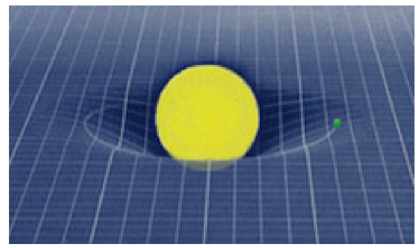


forced to conclude that gravitational fields must also distort, or warp, space.

This is the solution that eluded Newton—gravity is not a spooky force that acts instantly over distances in a static spatial playing field. Gravity is a manifestation of the curvature of spacetime produced by the presence of mass. A star (see figure at right) has a gravitational influence on its surroundings because its mass distorts the shape of the spacetime in the vicinity of the star. The greater the mass, the greater the curvature of spacetime.



This curvature is also responsible for the influence gravity has on orbital dynamics. A planet orbits a star because the planet moves through the curved spacetime of a star (see figure at right.) In the mathematical representation of spacetime, the planet moves along the "straightest" (shortest) path in curved spacetime. In another sense, Newton's force of gravity on the macroscopic scale is a fictitious force—it is not some spooky "action" between to objects of mass, but rather an interaction produced by movement through curved spacetime.

The Speed of Gravity

If the Sun were to suddenly disappear, its last light rays would race outward through space at exactly the same speed that the gravitational "rebound" of spacetime would. That rebound would be perceived as a gravitational wave rippling through spacetime much like a ripple races outward from the point where a rock is dropped into a pond. Hence, the visual disappearance of the Sun 500 seconds after the fact would coincide exactly with the "felt" disappearance of the Sun's gravitational influence.

confirming the accuracy of the initial measurement and calculation.

Marianne now states that they—or rather, she—must repeat the measurements in a second trial, but by this time the carousel has started and is rotating at 0.87*c* (87% of the speed of light!). Not wanting to carry her lab partner through the entire experiment, Marianne puts Ginger to work measuring the radius while she takes a break and sits at the center. When Ginger reaches the edge, she agrees that the radius of the carousel is indeed 10 meters. So far so good—the calculated circumference (62.8m) agrees with the first trial, but Marianne figures she better have Ginger measure the circumference directly as a final check. As Ginger sets out to measure the circumference by moving around the edge, Marianne watches carefully and soon begins to doubt her partner's ability to perform even this simple measurement. To Marianne's disbelief, Ginger confidently announces the circumference it 125.6 meters! Twice as large as the measurement Marianne made just a few minutes before.

How can that be? Even Ginger isn't so incompetent that she would get the circumference wrong by so much! Marianne thinks about what could be wrong while telling Ginger to try measuring the circumference again. As Ginger sets out to conduct the measurement of the circumference a second time, Marianne begins to realize the result is again as it should be—125.6 meters.

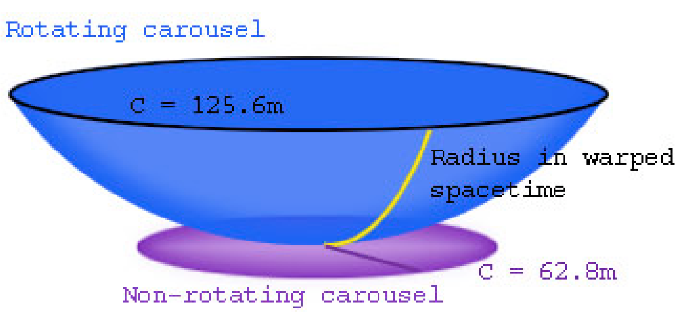
"Don't worry, I've got it. The number is right," Marianne exclaims confidently.

Ginger is baffled. How can both numbers be right?

The answer, Marianne explains, came to her when she noticed the background was moving. The carousel had been started after she sat down at the center and made Ginger start measuring. The measurement of the radius was unaffected since that measurement was *perpendicular* to the direction of the carousel's motion. Only when Ginger physically measured the circumference was she laying the meter stick *in the direction of the rotation*. Moving at 0.87*c*, the meter stick was contracted by 50% as predicted by the Lorentz transformations of special relativity! Thus, the number of lengths of the meter stick required to complete one circumference was twice as big as it was for the stationary carousel, or 125.6 meters. There is no error, just length contraction. Ginger didn't notice the length contraction since she was stationary with respect to the meterstick. Only Marianne, watching from the center of the rotating carousel, noticed the meterstick looked short.

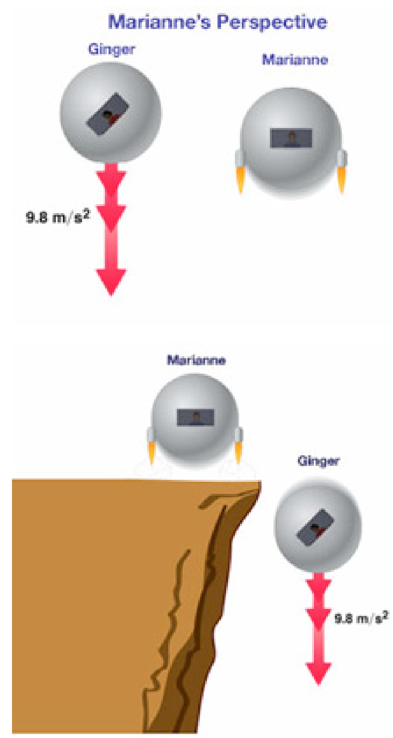
Acceleration as Warpage

If we were to envision this rotating carousel and plot its shape, the fact that the calculated circumference is 62.8 m and the measured circumference is 125.6 m would result in a "warped" carousel that is not flat like it was when it was stationary.



The rotating carousel is, in fact, accelerating since any point other than the center is constantly changing direction. Acceleration distorts measurements of space! Applying the Principle of Equivalence, we are

The equivalence principle allows the women to truly claim that all motion is indeed relative as Einstein had believed. When Ginger observes Marianne feel a force, she can claim that Marianne is accelerating away from her. Marianne, however, can claim with equal validity that both shuttlecrafts are in the presence of a gravitational field resulting in Marianne having a measurable weight. The only reason she isn't moving is because her rocket engines are allowing her to hover over the ground (See Figure 4.)



If she is in fact hovering over the ground, Marianne can then reason that Ginger is truly the one accelerating and the only reason she does not feel any force is or detect any acceleration with her instruments is because Ginger is in free-fall just like a skydiver would be after jumping out of an airplane but before the parachute is opened. It does, in fact, appear to be true that no experiment or measurement can be performed that would give absolute proof that an observer in stationary within a gravitational field or moving with constant acceleration in a zero-gravity (or more accurately, a micro-gravity) environment such as space.

THE RIDDLE OF GRAVITATION

Even after the realization that gravity and accelerated motion are indistinguishable and equivalent, Einstein was still troubled by a problem with the law of universal gravitation that plagued Newton and all scientists afterwards—just what was the nature of gravitation. In his *Principia*, Newton admitted that he could not "feign hypothesis" and that he would leave it to his successors to decipher the nature of gravitation. As envisioned by Newton and the scientists of the Enlightenment who followed, gravitation was a force that acted instantly over an distance. That lead to a troubling paradox, however, after the speed of light had been measured to be extremely fast, but finite.

Newton's Dirty Little Secret

Consider a troubling hypothetical situation in which the Sun instantly disappears. According to Newton's law of gravitation, the absence of the Sun's mass would instantly result in Earth and the other planets flying off into space because the Sun's gravitational influence on them was gone. The last rays of light leaving the Sun before it disappeared, however, would continue traveling outward and would reach Earth's orbit 500 seconds (8 minutes 20 seconds) later. *In other words, we would still see the Sun after it disappeared, but the change in Earth's orbit would tell us the Sun was no longer there!* How could it be there and NOT be there at the same time?

Einstein knew the answer had to be connected to the equivalence principle. Using the mathematics and postulates of special relativity he was able to pull all the pieces together**.**

Riding Along on a Carousel

Imagine that we have a very special carousel—one that can rotate at speeds very near the speed of light—and wish to determine its circumference. First, while the carousel is stationary, Ginger (being lazy and taking advantage of her lab partner's skills a bit too much) just watches and lets Marianne measure the distance from the center to the edge of the carousel with a meter stick. At the edge, Marianne announces the carousel's radius is 10 meters. Hence, its circumference is simply 62.8 meters (from $C = 2\pi r$). Being a thoughtful astronomy student, Marianne knows it's important to check "their" work by actually measuring the circumference of the carousel while Ginger, sitting at the center, watches her move around the edge with the meter stick. As expected, the measured circumference is indeed 62.8 meters,

THE GENERAL THEORY OF RELATIVITY

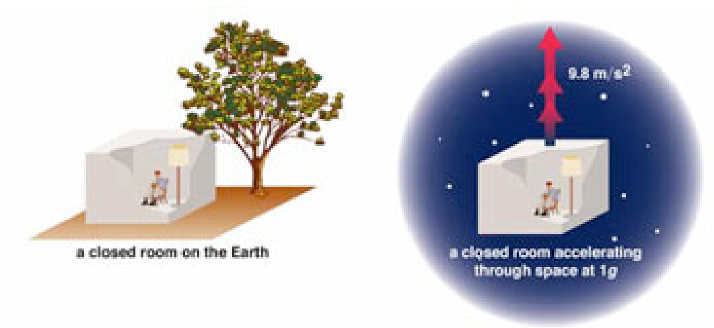
THE PRINCIPLE OF EQUIVILANCE

The theory of special relativity was necessary because it solved two important problems left over from the nineteenth century: the apparent constancy of the speed of light regardless of an observer's velocity relative to the beam of light and peculiarities in Maxwell's equations of electrodynamics that gave contradictory results concerning the induction of magnetic and electric fields between a moving magnet and a coil of wire (in fact, the title of Einstein's famous paper on special relativity is "On the Electrodynamics of Moving Bodies").

Special relativity shows there is no absolute answer to the question "Who is moving?" When two people pass each other at constant velocity, each with equal validity can claim to be at rest. Einstein wanted to believe that all motion is relative, however. Even those situations involving acceleration (a change in velocity). Inconsistencies arising from forces felt during acceleration troubled him since the claim of rest or motion at constant velocity could not be legitimately claimed for both observers.

A breakthrough came in 1907, however, when Einstein had what he later described as "the happiest thought" of his life: that whenever weight is felt, it can equally be attributed to the effects of acceleration or gravity. The Principle of Equivalence (see figure below) states that the effects of gravity are indistinguishable from those of accelerated motion.

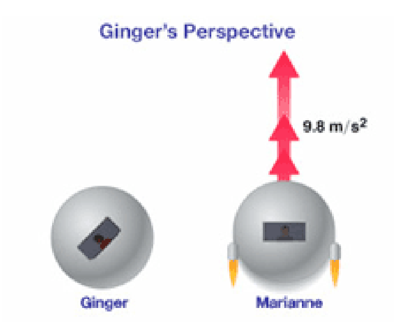
Indeed, scientists as far back as Newton knew of the similarities between the force of gravity and the forces of accelerated motion, but they believed them to be merely coincidental. Einstein imagined an inextricable connection. Stated more simply, the Principle of Equivalence says that a person isolated from the outside world can not tell if she is at rest in a gravitational field that results in a measurable weight or if she is out in space and accelerating.



No experiment can be performed, such as swinging a pendulum or dropping weights, to determine which state the woman is in since the experiments would yield the same results as if she were standing on Earth the entire time.

IT'S ALL RELATIVE

Consider a situation where Ginger and Marianne are in separate shuttlecrafts and Ginger sees Marianne moving away with ever greater velocity (see Figure 2.) In other words, she believes Marianne is accelerating away and her own shuttle is at rest.



Marianne might claim that she is at rest and Ginger is the one receding into the distance (see Figure 3), but the force felt by Marianne causes a problem. Ginger can look back at Marianne and say, "If I'm moving, why are you the one feeling a force? You have to be accelerating away from me!"